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STRUCTURAL EVALUATION OF ASPHALTIC PAVEMENTS

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ABSTRACT

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KEYWORDS: Asphaltic Pavements, Overlay Designs, Deflections, Deflection Bowl, Structural Condition, Nondestructive Testing, Pavement Evaluation, Subgrade Modulus, Asphaltic Concrete Modulus, Equivalent Axleloads

To evaluate projects involving approximately 200 route-miles of interstate and primary pavements in Kentucky and Tennessee in relatively short time frames, it was decided to test, analyze, and design overlays using test equipment (Road Rater) and procedures developed by the University of Kentucky Transportation Research Program. This paper presents the analysis methodology and the evaluation and overlay designs for selected projects, including the before-and-after analysis of milling on one project.

The Road Rater applies a dynamic sinusoidal loading of known force and frequency. The velocity of the vibration waves are measured by sensors and integrated electronically to obtain surface deflections. An analysis of the shape and magnitude of the deflection bowl permits an assessment of whether the structure is performing as anticipated or whether some component is significantly weaker than designed. Analyses permit the determination of the "behavioral" or effective thicknesses of the asphaltic concrete layers and the in-place subgrade moduli. Strip charts of overlay thicknesses for each test point along the length of a project permit delineation of the project into relatively uniform segments. The required overlay thickness is the difference between the total thickness required for new construction to carry the anticipated traffic and the behavioral thickness of the existing pavement.

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INTRODUCTION

Highway agencies for years have faced the problem of providing for the rehabilitation and rejuvenation of highway pavements. Typically, funds are insufficient to meet all such rehabilitation needs. In more recent years, the problem has been aggravated inasmuch as the great highway construction boom has now passed and all highway agencies, both state and local, are faced with a ballooned mileage of highways that must be maintained in a serviceable condition. Thus, the relative proportion of the rehabilitation budget requirements to the total highway agency budget has increased. A compounding factor is the general demand by the public that governmental agencies manage public funds more effectively and efficiently. Additionally, public monies available for all purposes are generally decreasing (relatively), and therefore the demand for allocation among various governmental services is much sharper and more competitive.

The transportation infrastructure, in part consisting of the highway and street networks of this country, are a primary element in economic development and growth. With such large concentrations of population in relatively small areas, it is absolutely necessary that required and desired goods and services be delivered to those that are not able to completely service themselves (and in today's era of specialization, almost no one is completely self-sufficient). There is now a tremendous burden on highway agencies to protect the great financial investment

represented by the highway and street systems. To make the most efficient use of available funds, it is necessary to select and schedule rehabilitation activities on a timely basis. If maintenance and rehabilitation are delayed, the level of service provided the traveling public decreases at an accelerating rate. Also, the cost of rehabilitation has been reported to be as much as four times that had the rehabilitation been performed at the proper time.

There are a number of tools and methodologies available to the highway engineer and administrator to assist in making decisions as to appropriate rehabilitation strategies. The most elemental and probably the first methodology to be used was to rely on visual surveys and observations of pavement conditions. Measurements of rutting and road roughness (ride quality) also have been used, along with measurements of the extent of cracking and patching, to provide input upon which to base decisions for rehabilitation activities. In more recent years, skid resistance of pavement surfaces has been involved in rehabilitation strategies. Unfortunately, these approaches of observing or measuring manifestations of pavement performance only from the surface are not always adequate. These traditional procedures may not show imminent, but hidden, structural deterioration.

Sometimes, to determine the actual structural capacity of a pavement system, it may be necessary to core the pavement. This, of course, is costly both in terms of funds and time and still may not provide the quantity of

information necessary to evaluate the structural capacity of a network of highways or streets. In recent years, pavement deflections (more specifically, dynamic deflections) have been used as an additional input variable to the decision-making process of selecting and scheduling rehabilitation strategies. Dynamic deflections made by such apparatus as the Road Rater, Dynaflect, and the falling-weight deflectometer provide basic information related directly to the structural adequacy of the pavement system. This information, along with the other more conventional input factors of pavement condition and performance, permits a more complete analysis of the sufficiency of pavement systems on a project-by-project basis; resulting decisions relating to rehabilitation strategies are much more efficient.

The objective of this paper is to summarize and document a methodology that has been developed to evaluate the structural adequacy of asphaltic concrete pavements prior to preparing overlay designs and recommending other rehabilitation strategies. The methodology is based on elastic theory and a rational pavement thickness design schema. The procedure makes use of dynamic pavement deflections measured by the Road Rater. It also has been demonstrated that pavement deflections obtained with the Dynaflect are compatible with the procedure. The methodology is "dynamic" inasmuch as it is continually being refined, and the description of the methodology contained in this paper is as of the spring of 1984. Case histories also

are presented to illustrate applications of the methodology to actual, "real-world" decisions related to overlay rehabilitation strategies.

BASIS FOR THE EVALUATION METHODOLOGY

SIMULATION OF DYNAMIC DEFLECTIONS

BY ELASTIC THEORY

Loading

The testing head of the Kentucky Road Rater consists of a vibrating mass of 72.6 kg (160 lb) that impulses the pavement; the forced motion of the pavement is measured by velocity sensors located at 0, 305, 610, and 914 mm (0, 1, 2, and 3 ft) from the center of the test head. Frequency of the vibrator may be chosen from 10, 20, 25, 30, or 40 Hz. When the vibrating mass is lowered to the pavement under a hydraulic pressure of 4.82 MPa (700 lbf/sq in.), the static load is 7.43 kN (1,670 lbf).

At a frequency of 25 Hz and a double-amplitude of vibration of 1.52 mm (0.06 in.), the Road Rater has a double-amplitude dynamic force oscillation of 2.67 kN (600 lbf). The composite loading consists of a static load of 7.43 kN and a dynamic force amplitude of 1.33 kN (300 lbf) that oscillates about the static load.

The Road Rater loading is transmitted to the pavement by two feet symmetrically located on either side of a beam that extends ahead and supports the velocity sensors. For these symmetrical conditions, deflection calculations need be made only for one foot and the radii corresponding to

each sensor location. Using superposition principles (1), deflections that result from the load applied to one foot must be added to deflections due to the load applied by the other foot to obtain the total deflection in the pavement at a given point.

The dynamic loading (sine wave) of the Road Rater may be approximated by a square wave such that the maximum value of the square wave is equal to $1/\sqrt{2}$ times the peak value of the sine wave. The maximum and minimum square-wave loadings for the Kentucky Road Rater are 8.37 and 6.49 kN (1,882 and 1,458 lbf). From symmetry, the maximum and minimum loads on each foot of the test head are equal to 4.19 and 3.24 kN (941 and 729 lbf), respectively. The total dynamic deflection is defined as twice the difference between the deflections calculated using the Chevron N-layered computer program (2) for the maximum and minimum loads.

Input Parameters

Inputs required by the Chevron N-layered program include a contact pressure corresponding to the applied load; the number of layers; and the thickness, Young's modulus, and Poisson's ratio of each layer. The contact pressures of the maximum and minimum loads were selected to maintain the correct area for each loading foot. Values used in simulating the Road Rater loadings and deflections are summarized in Table 1.

The modulus of a granular base (E_2) is a function of the moduli of the confining layers, i.e., the modulus of the asphaltic concrete (E_1) and the modulus of the subgrade

TABLE 1. PARAMETERS FOR SIMULATION OF
ROAD RATER LOADING

PARAMETER	VALUE
Poisson's Ratio	
Asphaltic concrete	0.40
Granular base	0.40
Subgrade	0.45
Contact Pressure (MPa)	
Low (3.24-kN) load	0.183
High (4.19-kN) load	0.231
Layer Thicknesses (mm)	
Asphaltic concrete	51 thru 355 (four increments)
Granular base	51 thru 659 (four increments)
Full-depth asphaltic concrete	102 thru 510 (eight increments)
Modulus of Elasticity (GPa)	
Asphaltic concrete	1.38 thru 13.80 (nine increments)
Subgrade	0.041 thru 0.41 (nine increments)

1 MPa = 145 lbf/sq in.

1 kN = 225 lbf

1 mm = 0.04 in.

(E_3). Estimation of the modulus of the crushed-stone layer may be determined from the relationship $E_2 = F \times E_3$, where there is an inverse linear relationship between $\log F$ and $\log E_3$. The ratio of E_2 to E_3 is equal to 2.8 at a California bearing ratio (CBR) of 7 and to 1 when E_1 equals E_3 ; i.e., $E_1 = E_2 = E_3$ (3, 4), the case of a Boussinesq semi-infinite half space. Laboratory triaxial testing also has indicated variations in modulus as a function of confining pressure. A modulus ratio of 2.8 (crushed-stone base to subgrade) at a CBR of 7 represents experience in Kentucky. The modulus of the subgrade (in lbf/sq in.) can be approximated by the product of CBR and 1500, a method of estimating moduli adequate for normal design considerations up to a CBR of about 17 to 20 (3-7).

Reference Conditions

The modulus of elasticity of asphaltic concrete varies as a function of frequency of loading and of temperature. Conditions for the current Kentucky thickness-design procedures and the method for conducting Benkelman beam (static) deflection tests correspond to a modulus of 3.31 GPa (480,000 lbf/sq in.) at 0.5 Hz and a pavement temperature of 21 C (70 F). A reference frequency of 25 Hz was selected for the Road Rater; the corresponding modulus of asphaltic concrete at 21 C is 8.27 GPa (1,200,000 lbf/sq in.), obtained using Figure 1. The equation presented in Figure 1 is a close approximation of results of laboratory testing by Shook and Kallas (8).

THE DEFLECTION BOWL

Analyses of pavement deflections involve examinations of the shapes of deflection bowls (6, 7, 9-17). The shapes of typical deflection bowls are illustrated in Figure 2. An empirical evaluation of the shape of a deflection bowl involves extrapolating a straight line through the Road Rater deflections of the No. 2 and No. 3 Sensors when log deflection is plotted as a function of the arithmetic distance from the load head. The deflection at the position corresponding to the No. 1 Sensor is the No. 1 projected deflection (1P in Figure 3, for example). The slope of the semi-log secant line, the difference between the No. 1 projected (1P) and the No. 1 Sensor (1M) deflections, and the magnitude of all deflections are all indicative of the shape of the deflection bowl.

Typically, there is a difference between the No. 1 projected and the No. 1 Sensor deflections, both for theoretical deflections (calculated using the Chevron N-layered program and design or as-constructed input parameters) and for field-measured deflections. Normally, differences between the No. 1 projected deflection and the No. 1 Sensor deflection for both theory and field measurements are the same (see Figure 3). However, when these differences are not the same, unanticipated behavior of the pavement system is indicated. For example, slab deterioration is suggested when field measurements indicate a No. 1 Sensor deflection greater than the No. 1 projected deflection and the difference between these values is

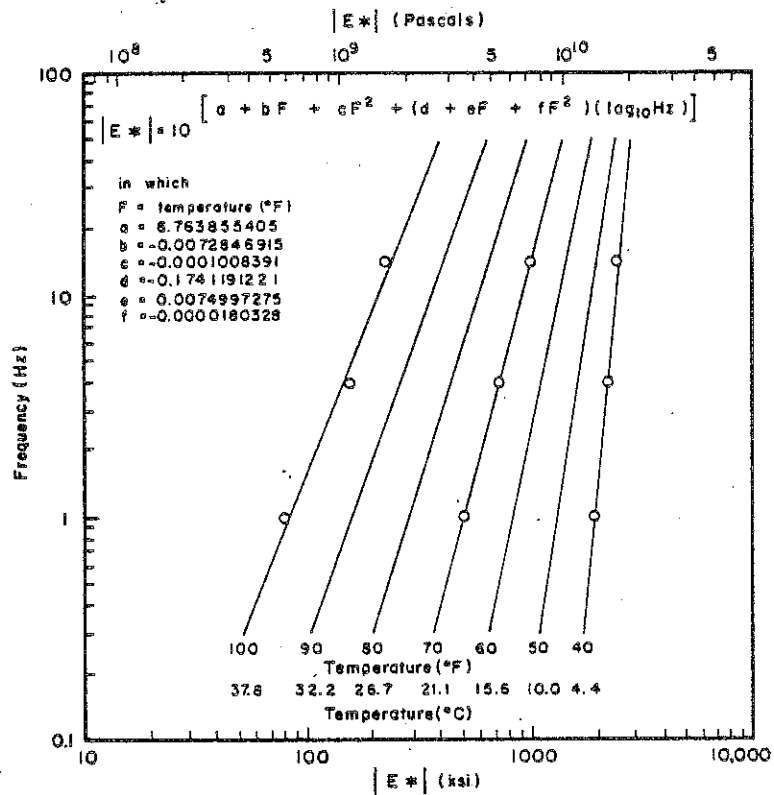


Figure 1. Relationships among Temperature of Pavement, Frequency of Loading, and Modulus of Elasticity of the Asphaltic Concrete.

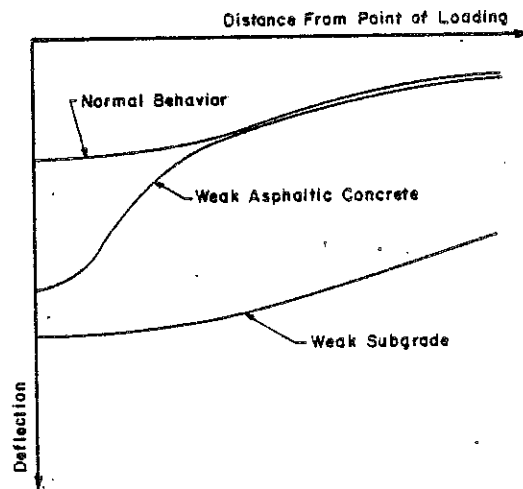


Figure 2. Sketches of Typical Deflection Bowls.

greater than the difference for theoretical deflections (see Figure 3). On the other hand, a foundation problem, or lack of supporting capability, may be indicated by increased magnitudes of all field deflections and a No. 1 projected deflection greater than the No. 1 Sensor deflection (see Figure 3). Also, the difference between the No. 1 projected deflection and the measured No. 1 deflection should be greater than the difference for theoretical deflections.

A log-log plot of No. 1 projected deflections versus No. 1 Sensor deflections may be used to identify variations in behavior of the pavement structure. The solid line in Figure 4 shows the theoretical relationship for a given structure and asphaltic concrete modulus. Subgrade modulus increases logarithmically (approximately) along the line as deflections decrease. The approximate logarithmic scale is a function of pavement structure. The two dashed lines indicate the variation in position of the theoretical line due to changes in magnitudes of the deflections by \pm one unit (2.54×10^{-4} mm or 1×10^{-5} in.) on the Road Rater meters and the associated shift in calculated No. 1 projected deflections. The zone inside these dashed lines represents an expected variation due to reading the meters of the Road Rater.

EFFECT OF ERRORS AND MISSING DATA

Current procedures utilize deflections of the three sensors nearest the point of load application to evaluate the shape of the deflection bowl. Comparisons between the

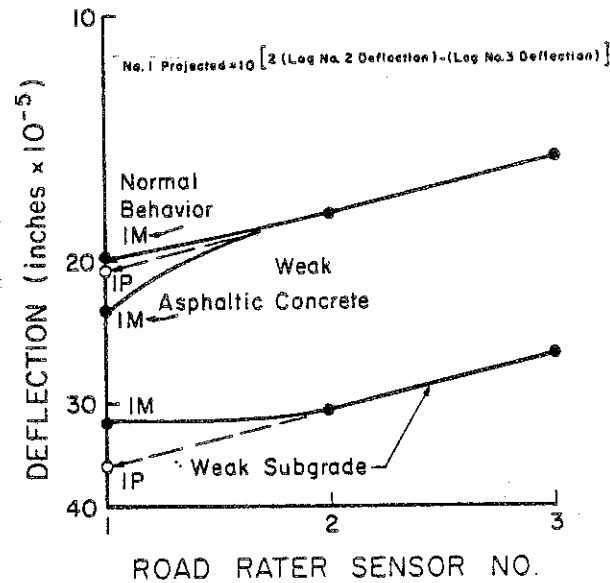


Figure 3. Surface Deflection as a Function of Distance from the Road Rater Load Head, Illustrating the Determination of the No. 1 Projected Deflection (1P).

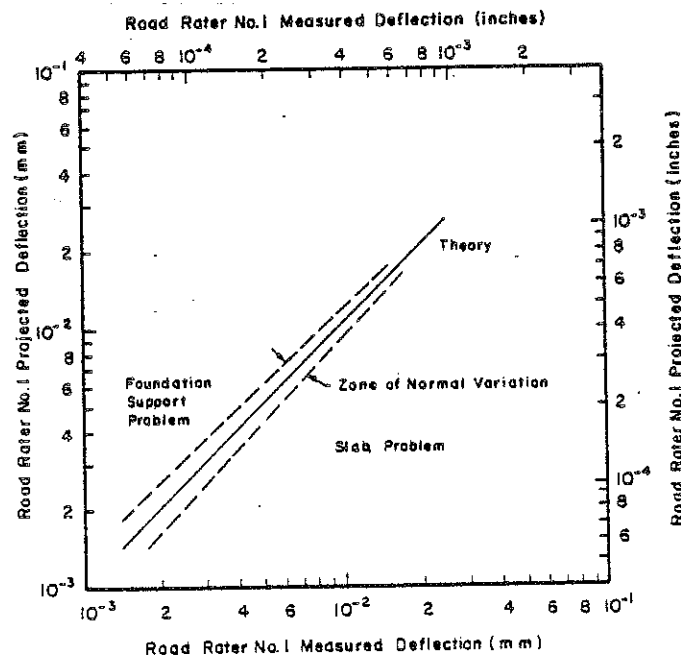


Figure 4. Relationship between Road Rater No. 1 Projected Deflection and Road Rater No. 1 Sensor Deflection (Measured).

shape of the measured deflection bowl and the theoretical bowl provide estimates of effective thicknesses and subgrade moduli. Since analysis of Road Rater data involves all deflections simultaneously, it is important to understand the effects of errors for any or all measurements.

Normal operating tolerance for reading the Road Rater meters is \pm one unit. The probability of the occurrence of an error of plus one unit or of minus one unit for any given sensor is $1/3$ (33.3 percent). However, the probability of the occurrence of an error in one sensor reading for a single set of readings (deflection bowl) is reduced to $1/9$ (11.1 percent) (nine possible combinations of a unit variation in reading a single scale or meter). The probability of the occurrence of an error of plus one unit or of minus one unit on two of the three Road Rater sensors for a single deflection bowl is $1/18$ (5.6 percent). The probability of the simultaneous occurrence of a similar error in all three sensor readings is even more remote ($1/27$ or 3.7 percent).

There are numerous combinations of errors of plus or minus one unit. Analyses have indicated that an error for the No. 2 Sensor is most critical for current analysis procedures. It also has been determined that errors of plus or minus one unit for the No. 2 Sensor in combination with and minus or plus one unit for the No. 3 Sensor are most critical when two errors occur simultaneously. The most critical simultaneous errors in all three sensor readings are minus or plus one unit for the No. 1 Sensor, plus or

minus one unit for the No. 2 Sensor, and minus or plus one unit for the No. 3 Sensor.

These errors in reading Road Rater meters affect predictions of the behavior of existing pavements. The extent of the effect is a function of the thickness and strength of each layer and the strength of the subgrade. Normal operator error affects more significantly the results of analyses when the magnitudes of deflections are small, because a unit change produces a greater change in predicted subgrade strength and(or) effective pavement thickness (see dashed lines in Figure 4).

Occasionally, situations arise such that data for one of the sensors may be missing or obviously erroneous. In that event, data may be analyzed using procedures published previously (7). The short-cut procedure reported in this paper is not applicable since that approach is predicated upon an analysis of both the shape and magnitude of the deflection bowl.

Table 2 illustrates a portion of deflection data where the the third sensor occasionally short circuited because of a broken wire in the cable connection. That condition was recognized and corrected, but not before a significant segment of the project had been tested. Information presented on the left portions of Table 2 are representative of typical output from a computerized analysis of Road Rater deflections utilizing the short-cut procedure. Note particularly the column labeled "ASPH T-EFF" and the very low magnitude of the effective thicknesses of asphaltic

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
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DESIGN THICKNESS = 6.50 INCHES

PREVIOUS 5-DAY AVERAGE TEMP = 79.3

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Sfc temp plus 5-day mean air history	Measured deflections Scale factor	Adjusted deflections Estimated subgrade modulus and effective thickness using Sensors No. 1, 2, and 3	Estimated subgrade modulus and effective thickness when data is missing or erroneous

concrete. An inspection of the unadjusted field deflection readings "SEN 1 RDG," "SEN 2 RDG," and "SEN 3 RDG" indicated the values for the third sensor were abnormally low for the specific pavement section being tested.

Since the short-cut analysis was not applicable, it was necessary to use deflections at the first and second sensors to estimate the subgrade modulus. A mean subgrade modulus may then be calculated and plotted as a function of the deflection at Sensor No. 1. Interpolation may be used to estimate the effective thickness of asphaltic concrete using the short-cut methodology. Results of those analyses are presented in the two columns to the far right of Table 2. Those results are more reasonable than for the short-cut analysis.

EVALUATION PROCEDURES

AS-CONSTRUCTED THICKNESSES

To properly evaluate the behavior of asphaltic concrete pavements, thicknesses of the component layers must be determined from the most reliable construction or maintenance records or by coring the pavement, if adequate records are not available. Analysis procedures are predicated on matching measured deflections with some theoretical deflection bowl. There are many combinations of layer thicknesses, layer moduli, and subgrade moduli that may result in a deflection bowl that matches field measurements. It is readily apparent that only a few of those combinations represent realistic configurations.

Initial procedures were of an iterative nature. More recently, procedures have been streamlined to eliminate the need for iterations. However, the existing layer thicknesses are necessary as a starting point for the analysis and also to assess whether results are realistic.

Specific portions of the analysis affected by the initial layer thicknesses include the following:

1. Estimation of the temperature distribution within the asphaltic concrete and the resulting mean pavement temperature (affects the magnitudes of the deflection adjustment factors and the average modulus of elasticity of the asphaltic concrete),
2. Estimation of the in-place subgrade modulus, and
3. Estimation of the appropriate worth (structural capacity) of the existing asphaltic concrete.

If the estimated as-constructed thicknesses are too thin, a hot summer day will result in a temperature distribution too high, an adjustment factor too large, an estimated subgrade modulus that is too high, and an equivalent thickness of asphaltic concrete too large. Conversely, assuming the as-constructed thickness of the asphaltic concrete greater than actual, the temperature distribution will result in a lower average temperature than expected, a lesser deflection adjustment factor, too weak a subgrade modulus, and too small an effective thickness of the asphaltic concrete. Fortunately, a given error in the assumed value of the as-constructed thickness of the crushed-stone base affects the estimate of the in-place subgrade modulus and behavioral

thickness of the asphaltic concrete much less than the same error in the as-constructed thickness of the asphaltic concrete.

ADJUSTMENTS FOR NONREFERENCE CONDITIONS

Moduli of Asphaltic Concrete

Field measurements include Road Rater deflections, surface temperatures, time of day, and frequency of vibration. The surface temperature, time of day, and mean air-temperature history for the previous five days are necessary to determine the temperature distributions within the pavement structure using a method developed by Southgate and Deen (18, 19). The five-day mean air-temperature history can be obtained from weather records at local offices of the National Oceanic and Atmospheric Administration or local radio and TV stations.

The mean modulus of elasticity of asphaltic concrete is a function of frequency of loading and mean pavement temperature (8, 20). A relationship between modulus and temperature may be developed for the reference frequency of 25 Hz, or any other frequency that may be representative of other dynamic loads (figure 1). Thus, a distribution of the modulus through the asphaltic concrete layer for the reference frequency of 25 Hz may be determined for any temperature distribution. For layers thinner than 152 mm (6 in.), results were better when the pavement modulus was taken as the average of the moduli on 12.7-mm (0.5-in.) intervals beginning at the 25.4-mm (1-in.) level. For

thicknesses greater than 152 mm, the most representative modulus appeared to be the mean of moduli on 25.4-mm intervals beginning at the 25.4-mm level. For pavements thicker than about 125 mm (5 in.), a mean of moduli at the top, middle, and bottom of the layer also was representative.

Adjustment Factors for Deflections

Because of the significant effect of temperature on the modulus of elasticity of asphaltic concrete, it is necessary to adjust deflection measurements to a reference temperature and modulus. One method of developing adjustment factors is to use ratios of deflections for variations in modulus and thickness of the asphaltic concrete layer and subgrade modulus. Such ratios can be used to adjust deflections to a reference condition. In Figure 1, the moduli at 21 C (selected as the reference in Kentucky) are 3.31 GPa for 0.5 Hz (Benkelman beam loading rate) and 8.27 GPa for 25 Hz (Road Rater loading rate). For a given thickness of asphaltic concrete, adjustment factors vary according to changes in the thicknesses of granular base and the values of E_3 , but these variations are minimal when compared with variations in adjustment factors for differences in thicknesses of asphaltic concrete layers. Thus, adjustment factors for all crushed-stone base thicknesses for a constant subgrade modulus and thickness of asphaltic concrete were averaged into a single line. Treating other thicknesses in the same manner produces similar relationships. Investigation of other subgrade moduli

indicated only minor variations in adjustment-factor values for the same thickness of asphaltic concrete. The adjustment-factor curves shown in Figure 5a were produced by averaging the adjustment factors for each thickness of asphaltic concrete and across subgrade moduli.

Two-layered pavements show similar variations in adjustment factors relative to E_3 's and asphaltic concrete thicknesses. The adjustment-factor curves shown in Figure 5b were produced by averaging adjustment factors for all E_3 's and a constant thickness of asphaltic concrete.

A mean pavement modulus can be found using the distribution of asphaltic concrete moduli through the pavement. The necessary adjustment factor (a multiplier) required to bring the field deflection to a deflection at a reference modulus is determined using the appropriate adjustment-factor chart (see Figure 5) and the mean modulus of elasticity of the asphaltic concrete layer.

An alternative method of presenting the adjustment factors is shown in Figure 6. The system shown adjusts the deflections to specific conditions -- 25 Hz, a mean pavement temperature of 21 C, and E_4 of 8.27 GPa. Figure 5 was developed on a basis of mean modulus of the asphaltic concrete layer. Figure 6 was developed from Figures 5a and 5b for more convenient direct adjustments on the basis of mean pavement temperatures. Factors from Figure 5 adjust Road Rater deflections to a reference modulus E of 8.27 GPa regardless of the frequency of loading. Factors from Figure

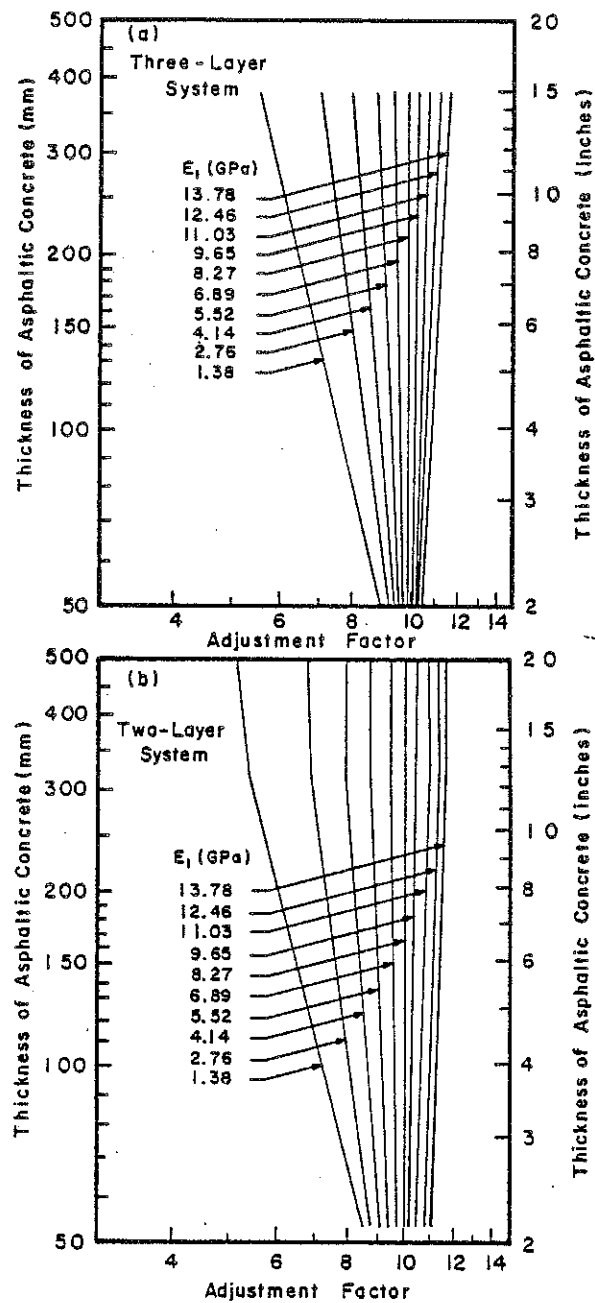


Figure 5. Relationship (for Sensor No. 1) between Thickness of Asphaltic Concrete and Temperature Adjustment Factor for (a) Three-layered Pavements and (b) Two-layered Pavements.

6 adjust Road Rater deflections to a reference temperature, frequency, and modulus (21 C, 25 Hz, and E of 8.27 GPa).

The adjustment-factor schema presented in Figures 5 and 6 was developed using theoretical deflection data corresponding to the No. 1 Sensor of the Road Rater. A similar system also was developed for deflection data for both the No. 2 and No. 3 Sensors. A comparison of the three different adjustment factors indicated an average difference of ± 0.032 between Sensors No. 1 and No. 2 and an average difference of ± 0.048 between Sensors No. 1 and No. 3 for a range of asphaltic concrete moduli of 1.38 to 13.8 GPa (200,000 to 2,000,000 lbf/sq in.). The greater differences in adjustment factors occurred at lower values of moduli and for thinner layers of asphaltic concrete. Initially, deflection adjustment-factor curves shown in Figures 5 and 6 were assumed to be adequate for any of the sensors (No. 1, No. 2, or No. 3) of the Kentucky Road Rater. However, experience has shown that use of a single adjustment factor for all sensors may lead to a skewed deflection bowl that may result in erroneous evaluations. Thus, separate adjustment factors now are used for each sensor. An equation representing the relationships in Figure 5 has been developed to calculate adjustment factors. The equation and coefficients for all sensors are presented in Table 3 (21).

Seasonal Adjustment

Figure 7 illustrates the variation in predicted subgrade moduli from April to September based on data obtained in Kentucky over a one-year period. Such analyses

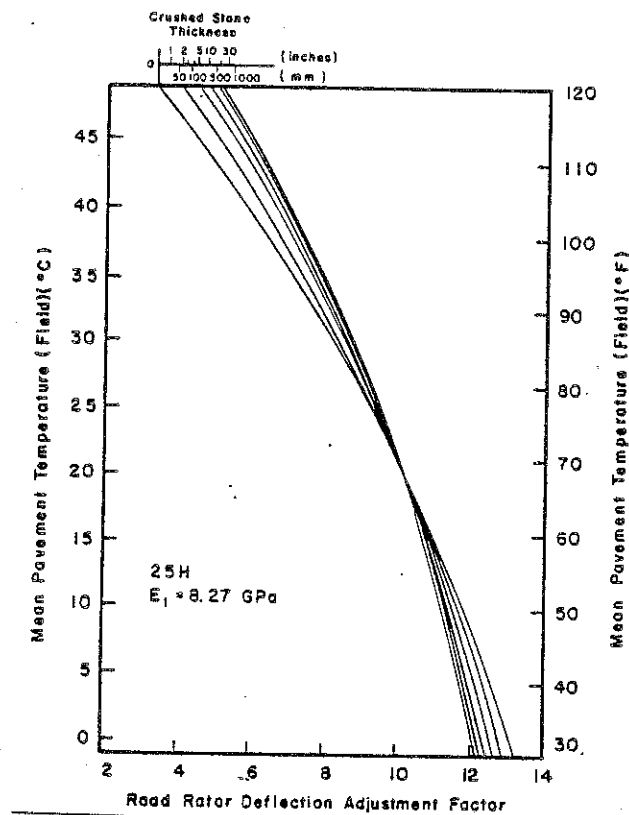


Figure 6. Relationship (for Sensor No. 1) between Mean Pavement Temperature and Road Rater Deflection Adjustment Factor at 21 C and 25 Hz.

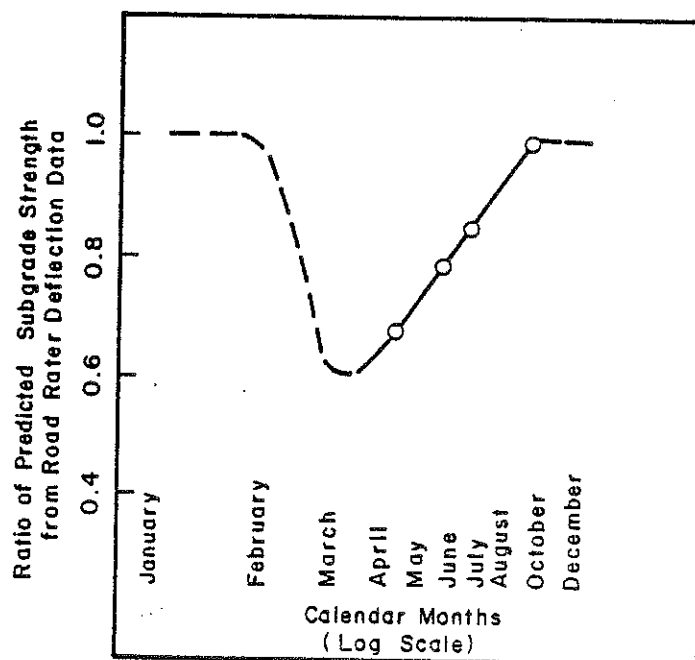


Figure 7. Subgrade Modulus as a Function of Time of Year.

TABLE 3. EQUATION AND CONSTANTS FOR DEFLECTION ADJUSTMENT
FACTORS FOR THE KENTUCKY ROAD RATER

$$\log AF = [\log AC - (H_1 E_{AC}^3 + H_2 E_{AC}^2 + H_3 E_{AC} + H_4)]$$

$$[M_1 E_{AC}^3 + M_2 E_{AC}^2 + M_3 E_{AC} + M_4]$$

in which AF = deflection adjustment factor,
AC = thickness of asphaltic concrete (inches),
E_{AC} = mean modulus of elasticity of asphaltic concrete
(psi), and
j = Road Rater sensor number (1, 2, 3).

THREE LAYERED PAVEMENTS

Crushed-Stone Base less than 8 inches thick

j	H ₁	H ₂	H ₃	H ₄
1	-2.0312535E-19	7.1127654E-13	-8.4587020E-07	0.25466949
2	7.2614981E-20	-1.0302809E-13	-1.3874220E-07	0.46069097
3	1.6419243E-19	-3.3570986E-13	-4.2060526E-08	0.66081522

j	M ₁	M ₂	M ₃	M ₄
1	1.0225763E-19	-4.4990262E-13	7.0628626E-07	-0.37155742
2	4.3336498E-20	-2.2091077E-13	4.5988841E-07	-0.30474423
3	3.3403716E-20	-1.6395133E-13	3.4805071E-07	-0.23820381

Crushed-Stone Base equal to or greater than 8 inches thick

j	H ₁	H ₂	H ₃	H ₄
1	-2.3472762E-20	1.1931522E-13	-2.9552194E-07	0.15345469
2	8.6274124E-20	-1.3810588E-13	-8.8295169E-08	0.42052283
3	1.1280263E-19	1.7456748E-13	-1.3783142E-07	0.60022647

j	M ₁	M ₂	M ₃	M ₄
1	8.6110078E-20	-3.8725065E-13	6.2848481E-07	-0.34173343
2	3.5850121E-20	-1.8167083E-13	3.8532939E-07	-0.25976352
3	2.1116466E-20	-1.0783377E-13	2.5034102E-07	-0.18049747

TWO LAYERED PAVEMENTS

j	H ₁	H ₂	H ₃	H ₄
1	-1.1966613E-18	3.6419900E-12	-3.3712189E-06	0.40220812
2	8.4194518E-20	-1.0803309E-13	-2.9750845E-07	0.63921054
3	2.8337843E-19	-6.0413664E-13	6.2056443E-08	0.84294820

j	M ₁	M ₂	M ₃	M ₄
1	1.0486807E-19	-4.5399608E-13	6.6726565E-07	-0.32106577
2	1.0429773E-19	-4.7586726E-13	7.9423008E-07	-0.44438965
3	9.6133265E-20	-3.9709184E-13	6.8153597E-07	-0.41509883

permit the adjustment of deflection data obtained at any time to equivalent springtime deflections, when the subgrade is typically in the weakest condition. Analyses of Kentucky data indicated that fall tests provide the most consistent long-term indicator of pavement behavior. However, overlay designs are based on the subgrade in its weakest condition. Thus, Figure 7 permits an approximate adjustment of test data to springtime conditions. Tests performed on interstate pavements in Tennessee from August through March confirmed the pattern of Figure 7. The minimum spring value for Tennessee was approximately 0.55 compared to 0.60 for Kentucky.

EVALUATION OF THE PAVEMENT STRUCTURE

Foundation (subgrade) stiffness (or modulus of elasticity) is a factor affecting the behavior of a pavement structure. Thus, estimates of subgrade strength are necessary to evaluate overall pavement conditions. A "design" condition exists when there is no loss of "effective" thickness in any of the layers. Deterioration or deficiencies in the layers of the structure means that performance is similar to another combination of layer thicknesses composed of reference-quality materials. In such cases, it is necessary to estimate the "effective" thicknesses of the deteriorated layers of the pavement structure. This may be accomplished by determining a realistic combination of layer thicknesses at reference conditions and subgrade modulus that results in a

theoretical deflection bowl matching the measured deflection bowl.

Estimating Subgrade Strength

For given layer thicknesses, relationships were developed (from elastic theory) between theoretical deflections and subgrade moduli for a constant (reference) asphaltic concrete modulus of elasticity (Figure 8 and Table 4). The methodology for utilizing these relationships to estimate subgrade strength has evolved through several stages. Initially, the first three sensor deflections were used to obtain three estimates of the subgrade modulus, which then were averaged. The methodology was simplified so only the No. 2 Sensor deflection was used (4, 7). Further refinements utilized the No. 2 and No. 3 deflections to compute a No. 1 projected deflection. The measured No. 1 Sensor deflection and the No. 1 projected deflection are then plotted and compared to values predicted by elastic theory.

Subgrade moduli may be estimated using deflections, measured by any of the sensors singly or in combination. Moduli may vary slightly, but those variations usually are not significant.

Interpretation of Deflection Data

Foundation or Subgrade Problems -- When a foundation problem exists, the deflection bowl is much "broader" and "flatter" than would be expected, and the magnitudes of all measured deflections are greater than those predicted by elastic theory for the anticipated design conditions (Figure

TABLE 4. EQUATIONS AND COEFFICIENTS FOR ROAD RATER DEFLECTIONS

$$\log \Delta = K \log E_s + L$$

$$K = N_1 AC^3 + N_2 AC^2 + N_3 AC + N_4$$

$$L = N_5 AC^3 + N_6 AC^2 + N_7 AC + N_8$$

$$N_i = A_i DGA^4 + B_i DGA^3 + C_i DGA^2 + D_i DGA + E_i$$

in which AC = thickness of asphaltic concrete (inches),

DGA = thickness of crushed-stone base (inches),

E_s = modulus of elasticity of the subgrade (psi), and

Δ = deflection.

i	A	B	C	D	E
NO. 1 SENSOR					
1	-8.0276712E-09	4.4637935E-07	-7.8334349E-06	4.3700774E-05	0.00015920
2	2.2880623E-07	-1.2956090E-05	0.00023168	-0.00126428	-0.00603433
3	-2.0069119E-06	0.00011636	-0.00213561	0.01152101	0.07053069
4	5.3511621E-06	-0.00032005	0.00617403	-0.03601869	-0.94738380
5	3.8112800E-08	-2.1142292E-06	3.6712485E-05	-0.00019713	-0.00079876
6	-1.0927940E-06	6.1604764E-05	-0.00108663	0.00564980	0.03181695
7	9.6888879E-06	-0.00055752	0.01004067	-0.05039463	-0.42286904
8	-2.6361517E-05	0.00155888	-0.02921499	0.14909581	6.27491080
NO. 2 SENSOR					
1	-1.9422702E-08	1.0770627E-06	-1.8518686E-05	9.5507480E-05	8.9416760E-05
2	5.2579366E-07	-2.9137271E-05	0.00049930	-0.00251336	-0.00416610
3	-4.2869807E-06	0.00023786	-0.00407118	0.01974778	0.07009015
4	9.8983780E-06	-0.00055346	0.00958628	-0.04540810	-1.12011456
5	6.1453952E-08	-3.3927169E-06	5.7851557E-05	-0.00028477	-0.00038341
6	-1.9486070E-06	0.00010728	-0.00180868	0.00847179	0.01804679
7	1.5831303E-05	-0.00087303	0.01469200	-0.06471592	-0.34277031
8	-3.6284025E-05	0.00202136	-0.03448633	0.13878339	6.61774653
NO. 3 SENSOR					
1	2.1333448E-08	-1.2598323E-06	2.4207689E-05	-0.00016422	4.6358157E-05
2	-6.1003392E-07	3.6138955E-05	-0.00069872	0.00483808	-0.00319426
3	5.4277510E-06	-0.00032212	0.00626602	-0.04474861	0.07028740
4	-1.5081292E-05	0.00089525	-0.01749993	0.13007837	-1.27529337
5	-1.0456648E-07	6.1644249E-06	-0.00011799	0.00078800	-0.00010359
6	2.9858350E-06	-0.00017641	0.00339148	-0.02303053	0.01019562
7	-2.6465435E-05	0.00156508	-0.03021266	0.21073267	-0.28067328
8	7.2699360E-05	-0.00429505	0.08308389	-0.60401394	6.84595514

2). In areas suspected of deficiencies in the subgrade and supporting (unbound) layers, tests indicated there was more variability among the deflections for No. 2 and No. 3 Sensors than among the measured deflections for the No. 1 Sensor. In such situations, either the No. 2 or No. 3 Sensor deflections, or both, and the associated No. 1 projected deflections are not matching elastic theory.

Deficiencies in Bound Layers -- Conversely, if there is a deficiency in the bound layer (asphaltic concrete), the deflection bowl bends sharply about the point of application of the load (Figure 2). The measured deflection at Sensor No. 1 is considerably greater than its theoretical counterpart while the No. 2 and No. 3 deflections very closely match predictions from elastic theory. Deflection bowls of this shape are usually observed where there are signs of pavement distress such as cracking and rutting.

Quantifying Effective Behavior -- Measured Road Rater deflection bowls can be evaluated by comparing to theoretically expected relationships. Pavement behavior (or condition) can be given in terms of a predicted subgrade modulus, effective layer thicknesses, and effective moduli of the layers. The effective behavior may be expressed by any combination of these variables that matches the measured deflection bowl. In methodologies presented in this paper, pavement behavior is expressed in terms of a predicted subgrade modulus and an effective thickness of "reference" high-quality asphaltic concrete. The effective thickness of

the granular base is assumed to be equal to the as-constructed thickness.

Determining a "true" and reasonable effective structure of an existing pavement is an iterative process. The reasonableness of the combinations of subgrade strengths and effective thicknesses of the asphaltic concrete is dependent upon the physical constraints (measured deflections and as-constructed thicknesses) of a given pavement structure. The iterative process involves selecting a subgrade modulus and effective thickness and comparing the resulting theoretical deflection bowl to the measured bowl. If the deflection bowls do not match, the subgrade modulus and effective thicknesses are adjusted and the process repeated until a satisfactory match is obtained.

Figure 9 (a combination of Figures 4 and 8) illustrates a "short-cut" procedure that usually eliminates the need for iterations. The methodology utilizes the theoretical relationship between No. 1 projected deflections and No. 1 Sensor deflections and the theoretical relationship between subgrade moduli of elasticity and No. 1 Sensor deflections.

Elastic theory has been used to simulate the relationship of surface deflection at the position of the No. 1 Sensor as a function of subgrade modulus, thickness of a crushed-stone base, and thickness of asphaltic concrete. The constructed thickness of asphaltic concrete will result in a relationship having the lowest deflection for a given subgrade modulus. Theoretically, as the pavement becomes thinner, the deflection will increase. Thus, a family of

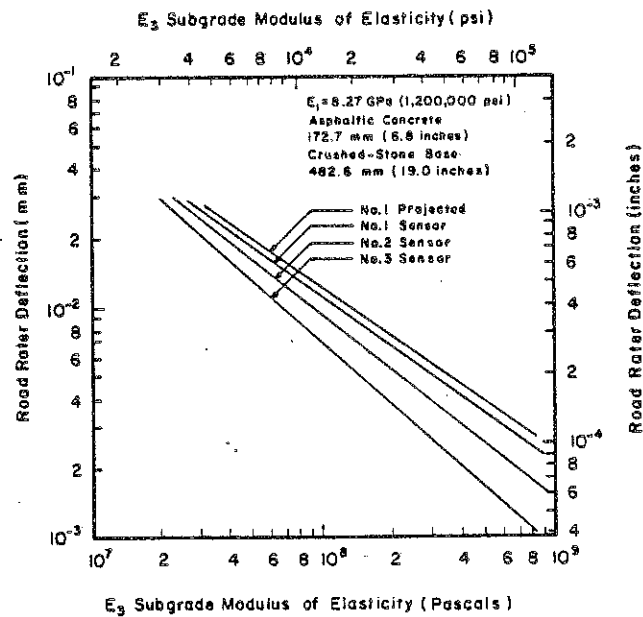


Figure 8. Theoretical Relationships between Road Rater Deflection and Subgrade Modulus of Elasticity for a Given Pavement Structure and Asphaltic Concrete Modulus.

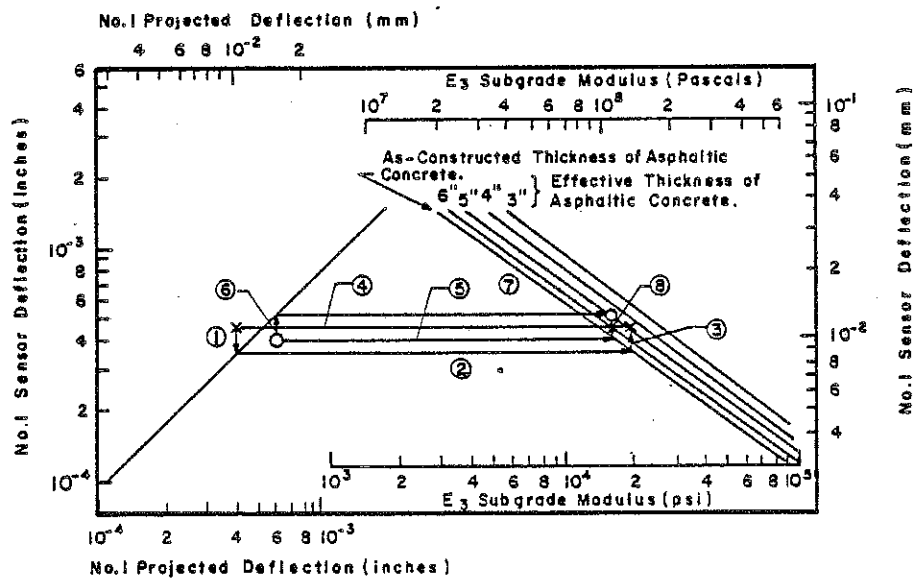


Figure 9. Illustration of a Method for Estimating In-place Subgrade Modulus and Effective Thickness of Asphaltic Concrete.

lines can be constructed to relate theoretical deflection of the No. 1 Sensor, subgrade modulus, and thickness of asphaltic concrete as shown on the right side of Figure 9. Table 4 summarizes the equations and coefficients of the family of curves.

Deflections for the second and third sensors are used to calculate a projected deflection for the position of the No. 1 Sensor (see section entitled THE DEFLECTION BOWL). A theoretical relationship between No. 1 Sensor deflections and projected deflections for constructed thicknesses of asphaltic concrete at reference conditions is illustrated by the solid line on the left portion of Figure 9 (also see Figure 4). Deflections measured by the second and third sensors are more indicative of the condition of the subgrade. Deflections of the No. 1 Sensor are indicative of the condition of the asphaltic concrete layer.

For the "x" point in Figure 9, deflections for the second and third sensors produced a calculated projected deflection too small when compared to the companion measured deflection for the No. 1 Sensor. This "abnormal" condition indicates the asphaltic concrete is performing as a thinner layer. If the measured deflection for the No. 1 Sensor is used to estimate the subgrade modulus, the effective behavior is as if the full thickness of the asphaltic concrete were on a weaker subgrade. In that case, the measured deflections for the second and third sensors would not match the theoretical deflections. Therefore, it is necessary to "correct" the "measured" projected deflection

to be compatible with deflections at the second and third sensors on the basis of the theoretical relationship between projected deflections and No. 1 Sensor deflections (left side of Figure 9). However, the deflection of the first sensor indicates the thickness of the asphaltic concrete is thinner than the actual thickness. To duplicate the measured deflection bowl, the equivalent structure that matches the condition is one of a thinner asphaltic concrete layer on a stronger subgrade. To obtain that structure having an equivalent behavior, the theoretical deflection is determined by moving vertically from the calculated projected deflection to the solid line on the left side of Figure 9 (Step 1). Using that point as a turn, move horizontally (Step 2) to obtain the estimated in-place subgrade modulus from the theoretical relationship between deflection and subgrade modulus for the constructed thickness of asphaltic concrete (heavy line on the right side of Figure 9). Using that estimated subgrade modulus as a turning point, move vertically (Step 3) to the measured deflection (Step 4) for the No. 1 Sensor to obtain the estimated thickness of the asphaltic concrete (from the lighter solid lines on the right side of Figure 9).

The other most commonly measured deflection bowl is illustrated by the "o" point in Figure 9. There the deflection bowl is very flat, normally indicating a weak subgrade condition. When deflection bowls of this sort are encountered, the magnitudes of the deflections at the second and third sensors are much larger than theoretically

expected and are not compatible with the measured No. 1 deflection. Therefore, it is again necessary to "correct" the measured deflection at the first sensor to be compatible with companion measurements for Sensors No. 2 and No. 3. Since the measured deflections at the second and third sensors are indicating a weakened subgrade, the unadjusted measurements are first used to estimate an in-place subgrade strength by moving horizontally along the value of the measured deflection of the No. 1 Sensor to the heavy solid line on the right side of Figure 9 (Step 5). The adjusted deflection for the first sensor (found by moving vertically from the measured deflection to the solid line on the left side of Figure 9 (Step 6) to locate another turning point) is used to estimate an effective thickness of asphaltic concrete (Steps 7 and 8). Comparisons with earlier analyses (5, 15) indicate that this procedure will normally result in a slightly stronger subgrade modulus coupled with a reduced asphaltic concrete thickness that produces a theoretical deflection bowl matching the measured bowl.

Analyses of field deflections indicated this procedure will produce results that can be used as input into an overlay design process without iteration. Road Rater testing of pavements before and after overlaying shows the ultimate behavior of the overlaid pavement is equal to that of a pavement having a total thickness of reference-quality asphaltic concrete equal to the sum of the effective thickness before overlaying and the overlay thickness (4, 7).

Estimation of Effective Structure

The determination of the effective pavement structure is illustrated by the right side of Figure 9. If the pavement is performing as one having a thickness equal to or greater than the design thickness of asphaltic concrete, the field data will plot on the theoretical line. If the field data plot above the line, the pavement is performing as one made of the reference materials but that is thinner than the design and(or) constructed thickness.

When pavement performance is expressed in terms of reduced layer thicknesses, all layers may be varied in any combination of thickness of reference materials and a predicted subgrade modulus that result in a deflection bowl matching the measured bowl. The present procedure, however, maintains a constant crushed-stone thickness (equal to the as-constructed thickness) and expresses pavement behavior as a reduced thickness of asphaltic concrete at the reference modulus. If this method is used, lines of reduced thickness of asphaltic concrete can be superimposed onto the plot of No. 1 Sensor deflection versus subgrade modulus. The effective thickness may be interpolated from those lines (right side of Figure 9).

Sampling and Statistics

The sampling interval for deflection testing varies according to specific analysis requirements. For example, the density of testing can be low when the objective is to estimate effective pavement behavior for long lengths of highway. The current density of testing for analysis of

asphaltic concrete pavements for overlay design purposes is at 0.16-km (0.1-mile) intervals for each direction or lane tested. Generally, overlay thicknesses are not varied in short lengths, and therefore, low-density testing is acceptable. If a specific problem area is to be evaluated, higher densities of testing may be required to delineate the limits of the problem area. In such cases, testing has been done on 30-m (100-ft), or less, intervals.

Statistical analyses of the results of the evaluation of deflection data (i.e., expressions of in-place behavior such as effective pavement thickness or subgrade strength) are normally oriented toward the selection of design values. It is desirable to select some level of pavement performance (required overlay thickness) that represents a tolerable balance between some overdesign and some acceptable risk of premature failure. For example, use of mean values for design purposes recognizes a 50-percent probability of premature failure. The design curves (Figure 10) used in Kentucky are based on the 90-percentile level (i.e., there is assumed to be only a 10-percent probability of premature failure). The statistical levels assigned to other aspects of the evaluation of the structural adequacy of pavements (effective thicknesses and in-place subgrade moduli) can be varied, depending upon the type of facility under consideration, the funds available for rehabilitation, and the degree of risk acceptable to the highway design engineer and administrator. Unfortunately, there is very

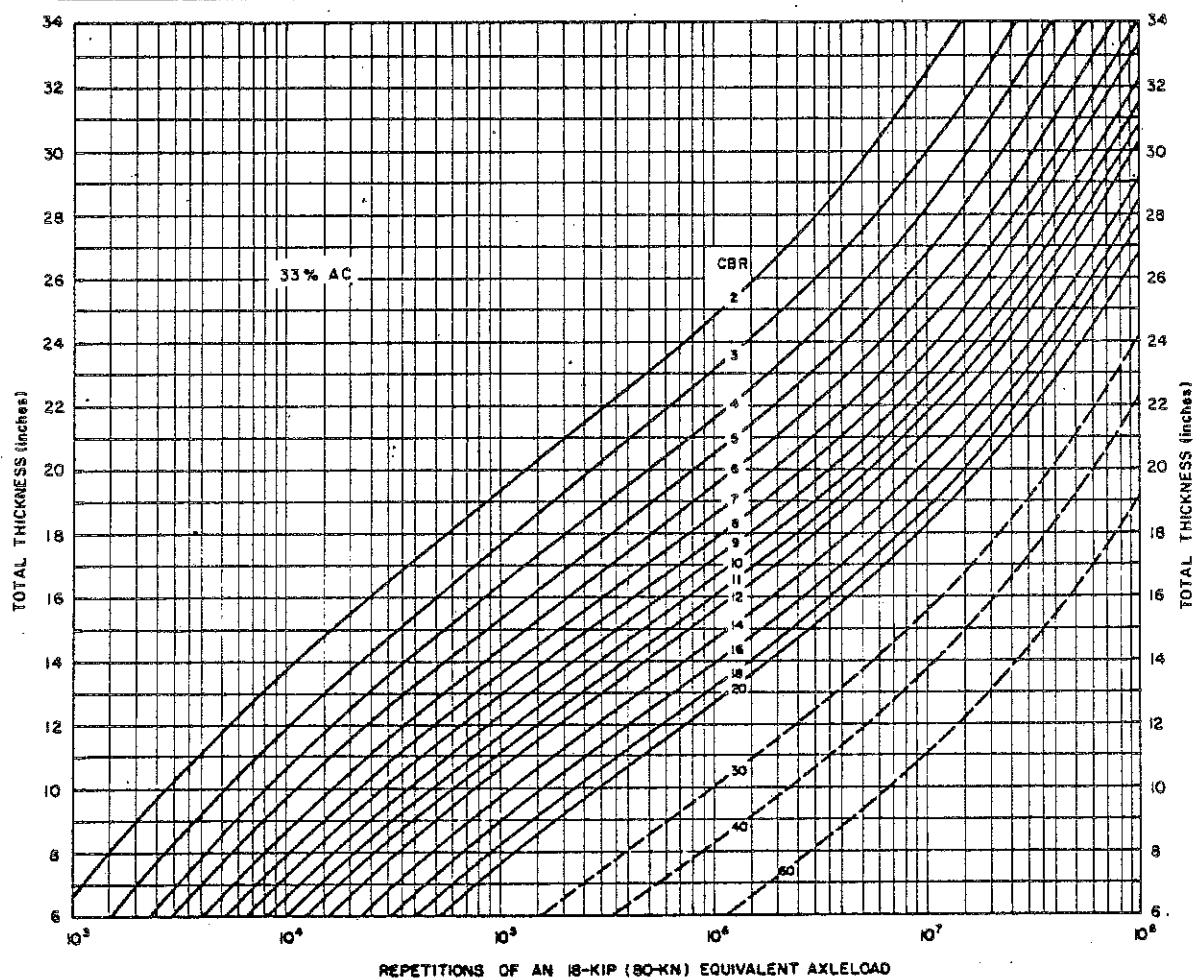


Figure 10. Simplified Design Curves for Thickness of Asphaltic Concrete Layer (a) 33 Percent, (b) 50 Percent, and (c) 75 Percent of the Total Pavement Thickness.

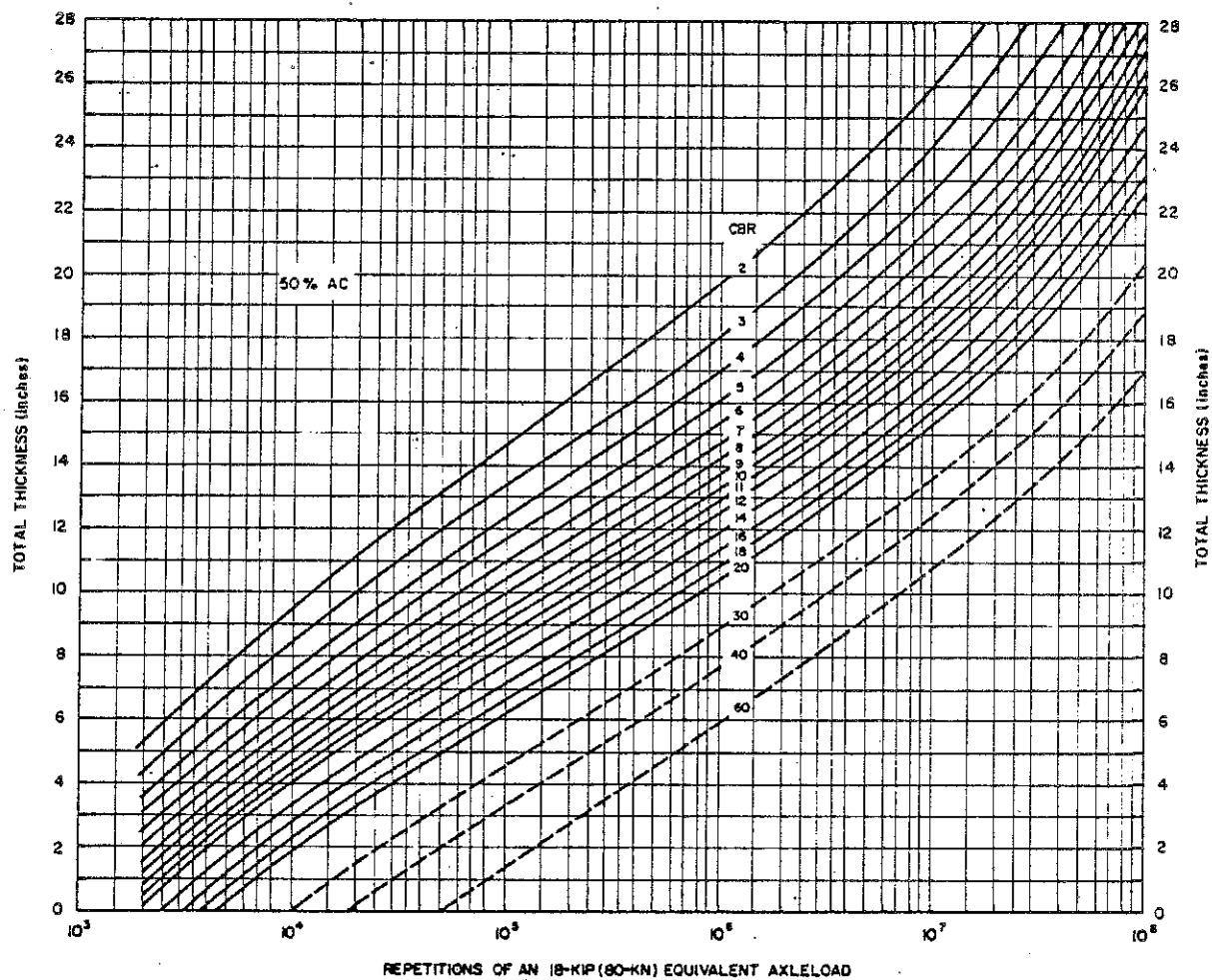


Figure 10. (Continued)

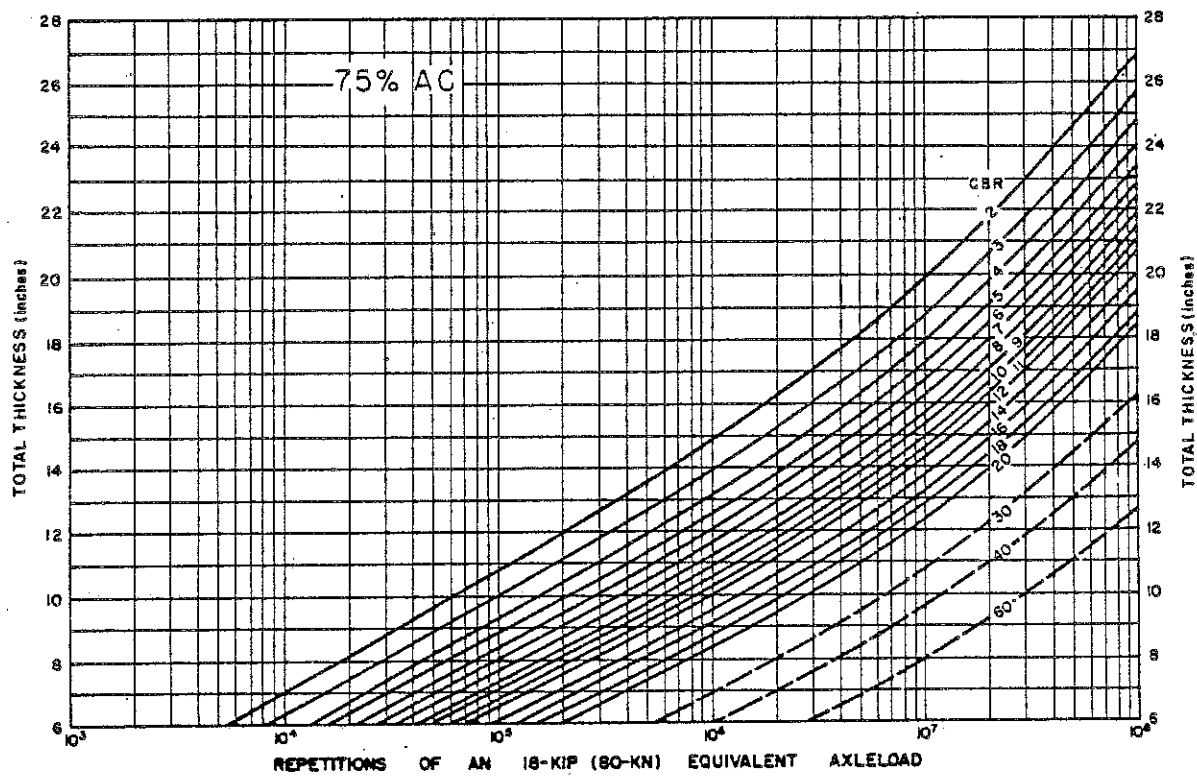


Figure 10. (Continued)

little documented experience relative to specific design confidence levels based on field performance histories.

The larger the sample size, the greater the reliability that may be attributed to the data analysis. A sample size of 30 or more measurements (of deflection bowls) is generally required for most statistics to be considered acceptable, although there are no firm rules regarding sample size. However, the assumption of a normal distribution is more valid with larger sample sizes.

DESIGN EQUIVALENT AXLELOADS

To prepare an overlay design, it is necessary to estimate or predict the characteristics of the anticipated traffic stream that is to be served by the section of highway under consideration. To use Kentucky's current thickness design procedures, the characteristics of the traffic stream must be expressed in terms of equivalent 80-kN (18-kip) axleloads (EAL's) anticipated during the design period. Several procedures are available to obtain such estimates (3, 4, 22).

OVERLAY DESIGNS

Once the input parameters (in-place subgrade moduli, effective thicknesses of asphaltic concrete, and design EAL's) have been determined for each test point by analyses of deflection and traffic data, overlay designs can be prepared. First, from Figure 10, determine the total structural thicknesses for at least three designs using the

existing thickness of the crushed-stone base. Plot and connect those points to obtain Curve A in Figure 11. For the design EAL and in-place subgrade modulus, determine three total design thicknesses from Figure 10. Plot those designs on Figure 11 and connect to obtain Curve B. The intersection of Curves A and B is the required total thickness for the design conditions. Overlay requirements can be determined as the difference between the total thickness required for "new" construction (the intersection of Curves A and B) and the effective thickness of the existing pavement in the design length.

Once an overlay design for each test point using the in-place subgrade and effective thickness for that point has been determined, the overlay designs then may be plotted on a strip chart (Figure 12) and design sections of more or less uniform overlay requirements delineated. Statistical parameters (i.e., acceptable design risks) then are applied to select the overlay design for each section.

An inspection of strip charts similar to Figure 12 may reveal data points that apparently represent extremely weak pavement conditions (over short lengths) when compared to the majority of the data for the design section. In selecting the overlay design (by applying acceptable levels of risks), those "weak" points may be removed from the analysis of statistical parameters. Special structural patches, to be placed before overlaying, may be designed for those weak locations to return them at least to the design conditions for that section.

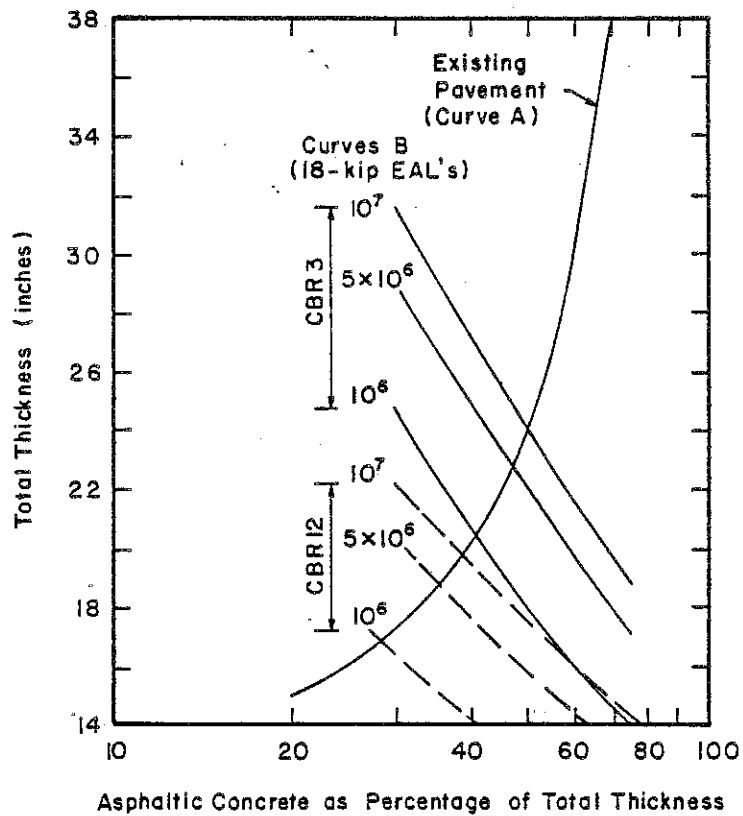


Figure 11. Example of Relationship between Total Design Thickness and Percentage of Total Thickness due to Asphaltic Concrete.

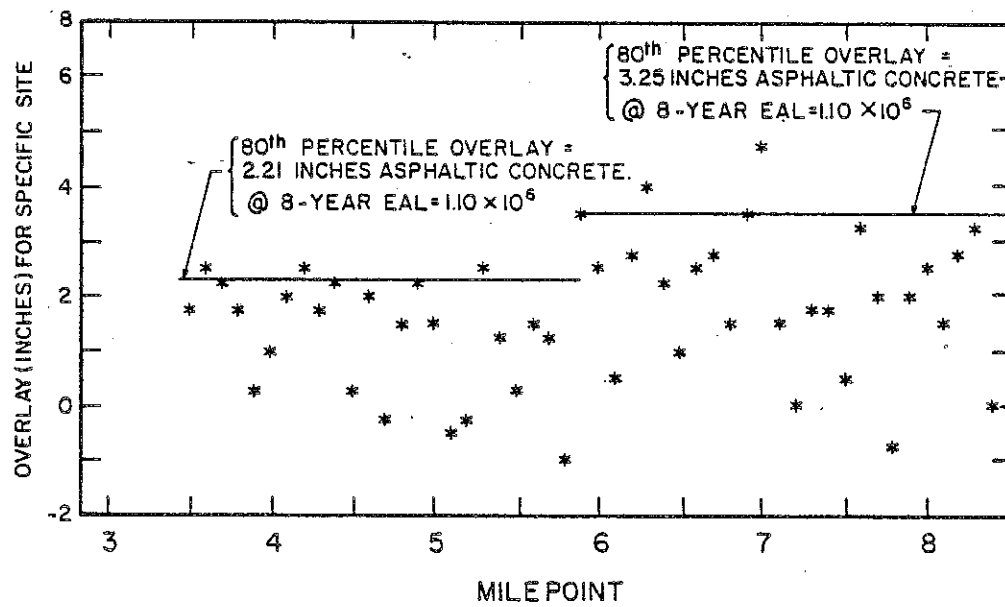


Figure 12. Strip Chart of Overlay Designs.

CASE HISTORIES

I 65, MARSHALL COUNTY, TENNESSEE

At the request of the Tennessee Department of Transportation, the Kentucky Road Rater and analysis procedures were used to evaluate the existing condition of a portion of I 65 in Marshall County. That analysis was accomplished prior to the preparation of overlay designs for the project. Estimates of in-place subgrade strengths and effective thicknesses were used to design overlays. Traffic data were provided by Tennessee officials. A sampling of the data-collection process and the results of the pavement evaluation are illustrated in Figures 13 through 17.

EVALUATION OF PAVEMENT MILLING

Deflection testing performed in August 1982 indicated a deteriorated condition in the asphaltic concrete layers on I 65 from MP 22.6 to 27.2 in Marshall County, Tennessee (a portion of the above project). It was decided to mill the top portion (76 mm (3 in.) of original construction and 25 mm (1 in.) of maintenance overlay) so that 235 mm (9.3 in.) of asphaltic concrete remained. Questions were raised concerning the structural worth of the material to be removed.

To assess the structural capacity of the milled material, Road Rater evaluations were conducted before and after milling. Deflection measurements were obtained during April and May 1983. Considering the difficulty of testing

DATA SHEET

PROJECT DESCRIPTION
AND
TEMPERATURE DISTRIBUTION DETERMINATION

Date: 8-4-82 Section: 4 MP 22.6 to MP 27.2

Projection Description: I65, MARSHALL COUNTY, TENNESSEE

NORTHBOUND MEDIAN (INSIDE) LANE

Beginning Time: 3:52 PM CST Temperature: 117 F

Ending Time: 4:26 PM CST Temperature: 112 F

Mean Pavement Surface Temperature: 114.5 F

5-day Mean Air Temperature History: 78 F

Sum: 192.5 F

Enter Temperature-Depth Curves with 4.00 (1600) and 192.5 F

Asphaltic Concrete Thickness: 12.3"

Temperatures at Surface: 114.5 F

Middle: 97 F

Bottom: 87 F

Mean Pavement Temperature: 99.5 F

Mean Modulus of Elasticity of Asphaltic Concrete: 310,000 psi
(at 25 Hz)

Deflection Adjustment Factors:

Sensor No. 1: 0.682

Sensor No. 2: 0.728

Sensor No. 3: 0.802

Figure 13. Project Description and Temperature
Distribution Determination.

DATA SHEET

DEFLECTIONS AND COMPUTATIONS

ODOMETER READING	TIME/ TEMP	LANE/ WHEEL TRACK	MEASURED DEFLECTIONS* SENSOR NO.				ADJUSTED DEFLECTIONS* SENSOR NO.				E SUB (ksi)	AC EFF T	
			1 2 3 4				1 2 3 1P					(in.)	1P**
79.5***	5:52pm	2 1	23	14	7	6	15.7	10.2	5.6	18.5	37.4	9.7	18.5
79.6	117 F	2 2	20	11	7	5	13.6	8.0	5.6	11.4	63.2	9.0	13.6
79.7		2 1	21	16	9	9	14.3	11.6	7.2	18.8	42.6	8.3	18.8
79.8****		2 2	32	23	10	6	21.8	16.7	8.0	35.0	23.4	5.8	38.2
79.9		2 1	26	16	10	7	17.7	11.6	8.0	16.9	37.2	10.3	17.7
80.0		2 2	55	37	18	13	37.5	26.9	14.4	50.3	11.0	6.9	58.6

NOTES:

Lane: 1 -- Outside lane

2 -- Inside (passing) lane

Wheel Track: 1 -- Outside

2 -- Inside

E SUB: Subgrade modulus (psi)

AC EFF T: Effective thickness of asphaltic concrete (inches)

* Deflection in 10^{-5} inches

** Theoretical projected No. 1 Sensor deflection in 10^{-5} inches

*** Milepoint 23

**** 1-inch patch on pavement at this point

Figure 14. Example of Data Sheet.

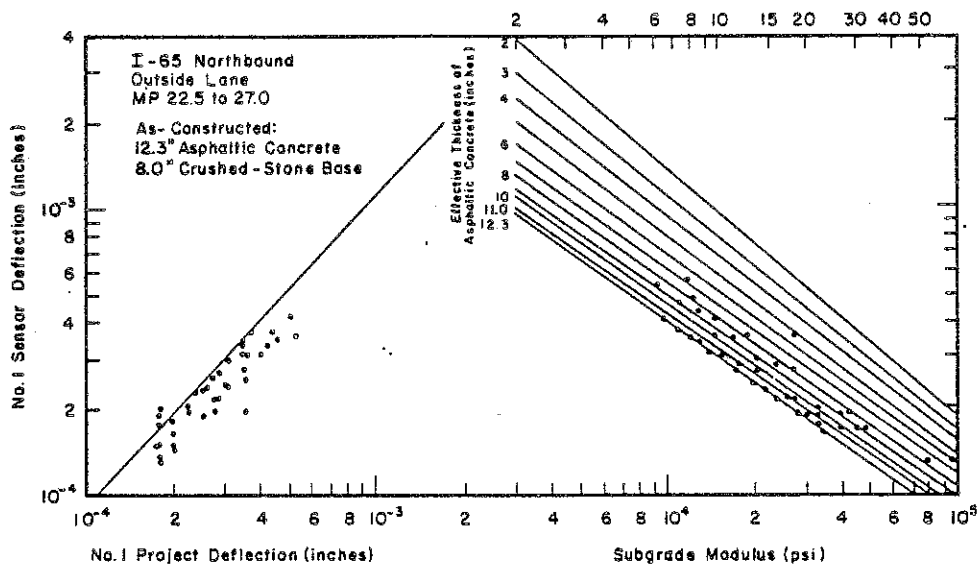


Figure 15. Graphical Determination of Subgrade Modulus and Effective Thickness of Asphaltic Concrete.

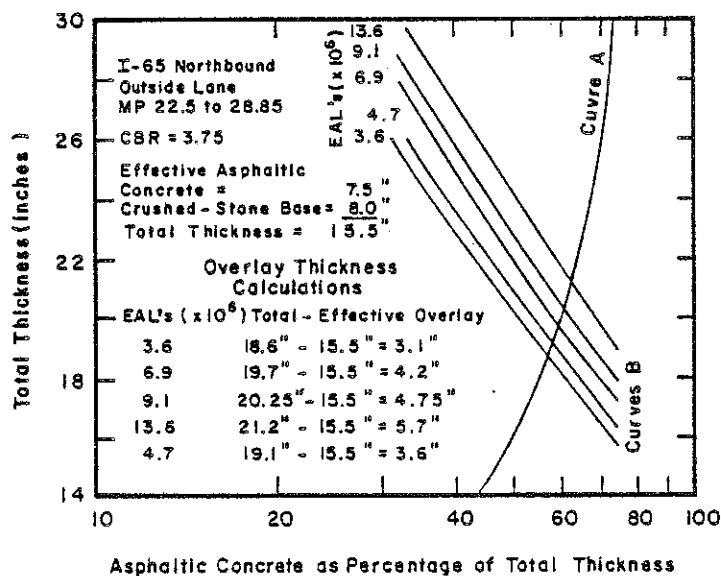


Figure 16. Determination of Overlay Thickness.

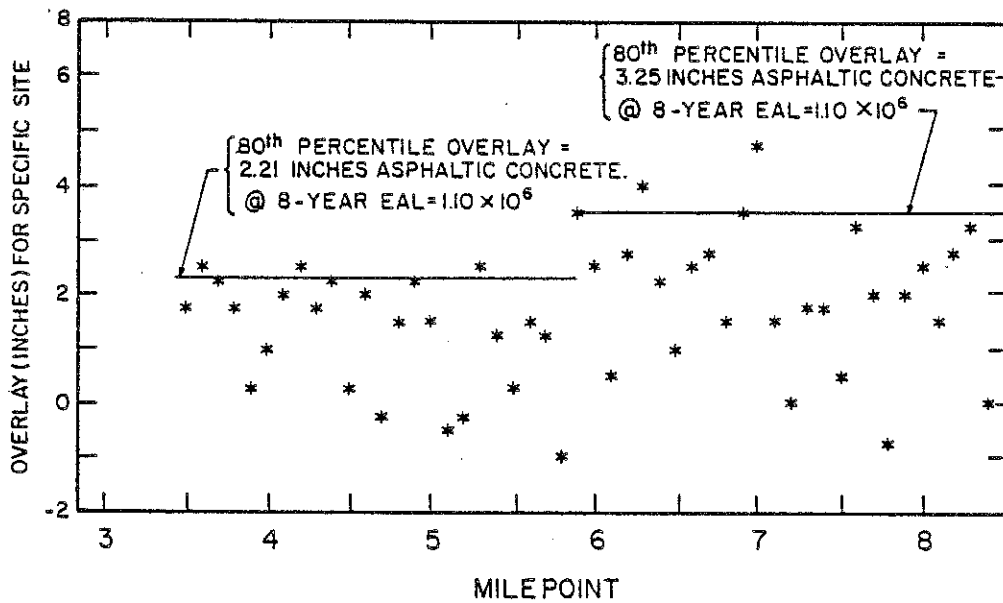


Figure 17. Strip Map of Overlay Designs.

the exact locations before and after milling, mean values were used for comparisons, rather than test point-by-test point comparisons. Table 5 summarizes results for each of three test lengths.

The difference between the effective behavioral thickness before milling and after milling was approximately 50 mm (2 in.), with slight variations depending on the particular test area. Thus, it was hypothesized that the milled material was worth structurally only 50 percent of the actual thickness removed by milling. It also was noted that the standard error was less after milling than before.

MAGOFFIN COUNTY, KENTUCKY

The Kentucky Transportation Research Program has been conducting an extensive deflection survey and analysis program for the Kentucky Department of Highways for the past two years to provide input into annual rehabilitation programs. Pavement roughness surveys and visual inspections are used to select sites for deflection testing. A recent example included in those activities was a section of KY 114 in Magoffin County. The segment of highway in question was constructed as 150 mm (6 in.) of asphaltic concrete on 300 mm (12 in.) of dense-graded aggregate base. The pavement is subject to considerable heavy coal-hauling traffic.

Road Rater deflection measurements were obtained at 0.16-km (0.1-mile) intervals during June 1983. Results of the analyses are presented in the left portions of Table 6. The spring CBR was computed by dividing the estimated

TABLE 5. EFFECTIVE THICKNESSES OF ASPHALTIC CONCRETE
BEFORE AND AFTER MILLING

LOCATION	NO. OF TESTS	THICKNESS (in.)		
		ACTUAL	BEHAVIORAL	
			MEAN	STANDARD ERROR
MP 23.6+ Outer Lane				
Before Milling	17	13.3	9.32	1.56
After Milling	17	9.3	7.40	0.86
Difference		4.0	1.92	
MP 23.7 to 24.1 Northbound Passing Lane				
Before Milling	84	13.3	9.78	1.74
After Milling	83	9.3	7.72	1.22
Difference		4.0	2.06	
MP 25.4 to 27.4 Northbound Outer Lane				
After Milling	81	9.3	7.69	1.08

1 in. = 25.4 mm

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	5
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DESIGN THICKNESS = 6.00 INCHES
MEAN TEMP = 95.1 AT TIME = 14.02
PREVIOUS 5-DAY AVERAGE TEMP = 79.6
MEASURED SURFACE TEMPERATURE = 105.0

SITE NO.	MILE-POINT	COMB TEMP	SEN1 RDG	SEN2 RDG	SEN3 RDG	RANGE	DEFL1	DEFL2	DEFL3	SUBGRAD MODULUS	ASPH T EFF	SPR CBR	IOL
1	0.00	184.6	41	27	12	1	31.98	23.80	11.48	27260	3.64	12.2	1.4
2	0.10	184.6	28	17	6	1	21.82	14.98	5.74	45983	2.27	12.6	3.6
3	0.20	184.6	40	26	8	1	31.14	22.90	7.65	28271	1.35	12.6	2.2
4	0.30	184.6	40	23	8	1	31.11	20.25	7.65	28308	2.78	12.2	2.5
5	0.40	184.6	41	25	9	1	31.86	22.01	8.60	27404	2.60	14.6	1.5
6	0.50	184.6	36	20	7	1	27.94	17.60	6.69	32781	3.06	11.5	1.9
7	0.60	184.6	43	23	8	1	33.35	20.23	7.64	25744	3.34	11.2	2.2
8	0.70	184.6	44	25	9	1	34.09	21.98	8.60	24980	3.16	9.6	-0.1
9	0.80	184.6	49	29	15	1	37.93	25.49	14.33	21589	5.70	7.5	1.4
10	0.90	184.6	59	41	23	1	45.62	36.03	21.97	16769	5.02	14.7	2.6
11	1.00	184.6	36	23	8	1	27.81	20.20	7.64	32996	1.96	7.7	4.2
12	1.10	184.6	58	36	12	1	44.76	31.61	11.46	17210	2.14	6.7	2.9
13	1.20	184.6	64	36	14	1	49.35	31.60	13.37	15062	3.86	6.3	3.3
14	1.30	184.6	67	40	16	1	51.61	35.10	15.27	14165	3.63	11.6	3.7
15	1.40	184.6	43	21	5	1	33.09	18.42	4.77	26012	1.49	7.4	4.1

SFC		Deflection		CBR	
Sfc temp plus 5-day mean air history _____	Measured deflections	Adjusted deflections	Estimated subgrade modulus and effective thickness using Sensors No. 1, 2, and 3 _____	Springtime CBR and overlay thickness for each test point	

subgrade modulus by 1500 and then multiplying by a factor (from Figure 7) dependent upon date of testing to adjust to springtime conditions. The column labeled "IOL" is the required overlay thickness for each test point. Statistical analyses may be applied to the individual overlay thicknesses to select an appropriate overlay design. Strip charts also may be prepared to determine locations where changes in overlay designs may be required or desirable. An 8-year design EAL of 1.33×10^6 was used in the analyses.

By March 1984, the analysis procedure had been modified to provide overlay thicknesses as a function of EAL's. A regression analysis is performed to determine this relationship for each design section of a project (Figure 18). This permits the preparation of overlay designs before project EAL's are estimated. An overlay design thickness is immediately available when the projected EAL is determined. Additionally, such overlay thickness-versus-EAL curves can be used to assess the impact of stage designs. Negative overlay requirements indicate the existing pavement structure is adequate for some time interval. An estimate of that interval can be obtained from the curves.

Figure 18a presents the relationship between overlay thickness requirements and 18-kip equivalent axleloads for a section of the Cumberland Parkway where deflection testing indicated a sound pavement condition. Note that nearly 10 EAL's may be sustained before the pavement fatigues structurally to the point of requiring an overlay. In Figure 18b is a similar relationship for a section of the

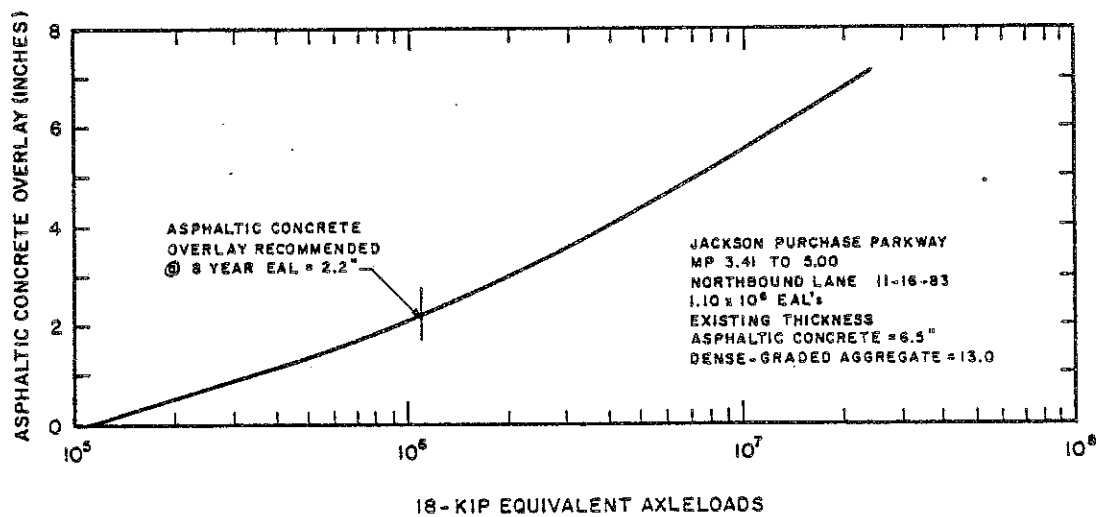
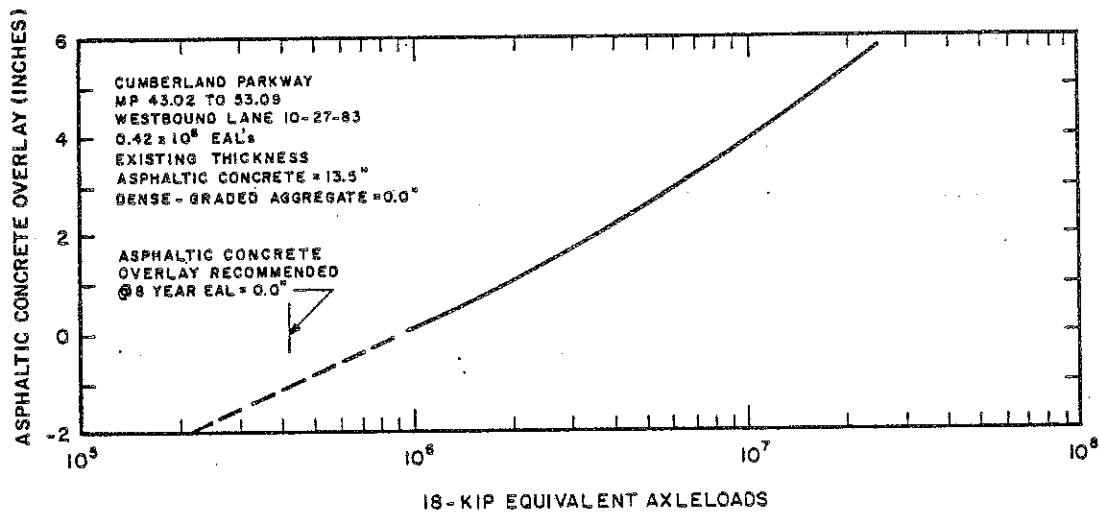


Figure 18. Overlay Designs as a Function of EAL.

Purchase Parkway where deflection testing indicated considerably greater deterioration. Rehabilitation is required immediately; delays in scheduling overlays for such pavements would result in accelerated deterioration that would require additional overlay.

OTHER APPLICATIONS

The concepts and procedures described in this paper have been applied to dynamic deflection data obtained directly on subgrades, on dense-graded aggregate bases, on pozzolanic bases, on full-depth asphaltic concrete pavements, and on portland cement concrete pavements. The Chevron N-layered program was used to develop for each case theoretical relationships between deflections and various combinations of layer thicknesses, Poisson's ratios, and moduli. The agreement between the theoretical relationships, Road Rater data, and laboratory data has been amazingly good (23).

The Chevron program also has been used to simulate the Road Rater for the analysis of broken and seated portland cement concrete pavements prior to and after overlaying. In-place subgrade moduli may be estimated from test data obtained on the intact pavement prior to breaking. Testing after breaking and seating provides estimates of moduli of the broken concrete, using the subgrade modulus obtained prior to breaking. The concepts discussed in this paper are being applied to these situations on an experimental basis. Many questions and relationships are being investigated.

Comparisons of sensor deflections from either side of a joint or crack in a portland cement concrete pavement may reveal the effectiveness of load transfer from slab to slab. Procedures utilizing Road Rater measurements for these evaluations are still being studied.

It also has been demonstrated that pavement deflections obtained with the Dynaflect can be analyzed utilizing the concepts presented in this paper. It is necessary, however, to develop relationships among sensor locations, deflections, moduli, and layer thicknesses that match the dynamic input of the Dynaflect.

CONCLUSION

Most approaches to analyzing deflection measurements of pavement systems require a large mainframe computer using iterative procedures to estimate the moduli of the layers. The results present the designer with the task of using those moduli to design overlay thicknesses. The approach presented in this paper greatly simplifies the task for the designer. The methodology offered can be processed by (and was, in fact, developed for) a programmable hand-held calculator. A program has been written for a mainframe computer to process deflection data using the methodology described in this paper. One advantage over processing by hand-held calculators is the significant savings in time to reduce the data. A second advantage is the availability of computerized statistical programs used in determining the

overlay thicknesses associated with specified design (risk) levels.

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The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented. The paper does not necessarily reflect the official views or policies of the University of Kentucky nor of any of the various supporters of the previous research. This paper does not constitute a standard, specification, or regulation.

REFERENCES

1. S. P. Timoshenko and J. N. Goodier, Theory of Elasticity, McGraw-Hill, New York, Third Edition, 1972.
2. J. Michelow, "Analyses of Stress and Displacements in N-Layered Elastic System under a Load Uniformly Distributed on a Circular Area," Chevron Oil Research, Richmond, California, September 24, 1963.
3. J. H. Havens, R. C. Deen, and H. F. Southgate, "Design Guide for Bituminous Concrete Pavement Structures,"

Transportation Research Program, University of Kentucky, Lexington, August 1981.

4. H. F. Southgate, R. C. Deen, and J. H. Havens, "Development of a Thickness Design System for Bituminous Concrete Pavements," Transportation Research Program, University of Kentucky, Lexington, November 1981.

5. M. W. Witczak, "Asphalt Pavement Performance at Baltimore-Washington International Airport," The Asphalt Institute, College Park, MD, Research Report 74-2, 1974.

6. M. W. Witczak, "A Comparison of Layer Theory Design Approaches to Observed Asphalt Airfield Pavement Performance," Proceedings, The Association of Asphalt Paving Technologists, Phoenix, Arizona, Vol 44, 1975.

7. G. W. Sharpe, H. F. Southgate, and R. C. Deen, "Pavement Evaluation Using Dynamic Deflections," Record 700, Transportation Research Board, Washington, DC, 1979.

8. J. F. Shook and B. F. Kallas, "Factors Influencing Dynamic Modulus of Asphalt Concrete," Proceedings, The Association of Asphalt Paving Technologists, Los Angeles, California, Vol 38, 1969.

9. R. W. Kinchen and W. H. Temple, "Asphaltic Concrete Overlays of Rigid and Flexible Pavements," Louisiana Department of Transportation and Development, Baton Rouge, September 1977.

10. K. Majidzadeh, "Dynamic Deflection Study for Pavement Condition Investigation," Ohio Department of Transportation, Columbus, 1974.

11. K. Majidzadeh, "Pavement Condition Evaluation Utilizing Dynamic Deflection Measurements," Ohio Department of Transportation, Columbus, 1977.

12. G. Peterson and L. W. Shepherd, "Deflection Analysis of Flexible Pavements," Utah State Highway Department, Salt Lake City, January 1972.

13. G. Peterson, "Predicting Performance of Pavements by Deflection," Utah State Highway Department, Salt Lake City, May 1975.

14. P. G. Rufford, "A Pavement Analysis and Structural Design Procedure Based on Deflection," Proceedings, Fourth International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, 1977.

15. H. F. Southgate, G. W. Sharpe, and R. C. Deen, "A Rational System for Design of Thickness of Asphalt Concrete Overlays," Record 700, Transportation Research Board, Washington, DC, 1979.

16. N. K. Vaswani, "Design of Flexible Pavements in Virginia Using AASHO Road Test Results," Record 291, Highway Research Board, Washington, DC, 1970.

17. G. Wiseman, J. Uzan, M. S. Hoffman, I. Ishai, and M. Livneh, "Simple Elastic Models for Pavement Evaluation Using Measured Surface Deflections Bowls," Proceedings, Fourth International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, 1977.

18. H. F. Southgate and R. C. Deen, "Temperature Distribution within Asphalt Pavements and Its Relationship

to Pavement Deflection," Record 291, Highway Research Board, Washington, DC, 1969.

19. H. F. Southgate and R. C. Deen, "Temperature Distribution within Asphalt Pavements," Record 549, Transportation Research Board, Washington, DC, 1975.

20. H. F. Southgate, R. C. Deen, J. H. Havens, and W. B. Drake, "Kentucky Research: A Flexible Pavement Design and Management System," Proceedings, Fourth International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, 1977.

21. H. F. Southgate, G. W. Sharpe, R. C. Deen, and J. H. Havens, "Structural Capacity of In-Place Asphaltic Concrete Pavements from Dynamic Deflections," Proceedings, Fifth International Conference on the Structural Design of Asphalt Pavements, The Delft University of Technology, Delft, The Netherlands, 1982.

22. J. A. Deacon and R. C. Deen, "Equivalent Axleloads for Pavement Design," Record 291, Highway Research Board, Washington, DC, 1969.

23. G. W. Sharpe, L. E. Epley, D. L. Allen, H. F. Southgate, and R. C. Deen, "Low-Strength Pozzolanic Materials for Highway Construction," presented to the Fall Meeting of the American Concrete Institute, Kansas City, Missouri, September 1983 (publication pending).

